Common Origin of Visible and Dark Universe

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Dark matter, baryonic matter and dark energy have different properties but contribute comparable energy density to the present Universe. We point out that they may have a common origin. As the dark energy has a scale far lower than all known scales in particle physics but very close to neutrino masses, while the excess matter over antimatter in the baryonic sector is probably related to the neutrino mass-generation, we unify the origin of dark and visible Universe in a variant of seesaw model. In our model (i) the dark matter relic density is a dark matter asymmetry emerged simultaneously with the baryon asymmetry from leptogenesis; (ii) the dark energy is due to a pseudo-Nambu-Goldstone-Boson associated with the neutrino mass-generation.

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Cosmological observations indicate that dark and visible matter contribute comparable energy density to the present Universe [1]. This coincidence implies that the dark and visible matter may have a common origin although their creation and evolution are usually understood by unrelated mechanisms. The visible matter exists in the present Universe as a matter–antimatter asymmetry, which is the same as the baryon asymmetry. If the amount of baryon and antibaryon were the same, they would have annihilated and we could not have existed. The most promising mechanism for generating a baryon asymmetry is leptogenesis [2, 3], in which a lepton asymmetry is first produced, which is then partially converted to a baryon asymmetry by the sphaleron [4] process before the electroweak phase transition.

In most models of dark matter, ones assume the dark matter to be a neutral particle without any quantum number, and then adjust its decay or annihilation rate to give a required relic density. There is another possibility that the dark matter actually carry some $U(1)$ quantum number so that the dark antimatter also exists. In this scenario, the excess of dark matter over dark antimatter could determine the amount of dark matter relic density if the dark matter and dark antimatter have very fast annihilation rate. This mechanism can explain the current existence of dark matter without fine tuning of the decay or annihilation rate of dark matter. The dark matter asymmetry could then be generated by the same mechanism that generates the baryon asymmetry [5, 6, 7, 8, 9]. Therefore, the visible and dark matter have a common origin which automatically implies their comparable energy density in the present Universe.

Cosmological observations also provide strong evidence that our Universe is expanding with an accelerated rate. This acceleration can be attributed to the existence of dark energy. It is striking that the dark energy scale is far lower than all known scales in particle physics except the neutrino masses. This coincidence may have its origin in the neutrino dark energy model [10, 11], where the dark energy is given by the pseudo-Nambu-Goldstone-bosons (pNGB) associated with the neutrino mass-generation [12, 13].

In this paper, we propose a variant of seesaw [14, 15] model to give a common origin for the visible and dark matter by creating the baryon and dark matter asymmetries simultaneously. At the same time this model explains how the dark energy is related to the neutrino masses, and hence, contributes comparable energy density to the present Universe with the visible and dark matter.

We start with a simple version of our model to focus on the common origin of the dark and baryonic matter. For simplicity, we do not write down the full Lagrangian, which is supposed to be invariant under a global symmetry of lepton number, instead we only give the part that is relevant for our discussions,

$$\mathcal{L}_{\mathrm{Y}} \supset -\frac{1}{2} y \overline{\psi_L^c} i\tau_2 \xi \psi_L + \mathrm{H.c.}\,, \tag{1}$$

$$\begin{aligned} V \supset\ & M_\eta^2 \left(\eta^\dagger \eta\right) + m_\xi^2 \mathrm{Tr}\left(\xi^\dagger \xi\right) + m_\chi^2 \left(\chi^\dagger \chi\right) \\ & + \left(\kappa \eta \phi^T i\tau_2 \xi \phi + \lambda \eta \chi^3 + \rho \eta \sigma^2 + \mathrm{H.c}\right) \\ & + \left(\chi^\dagger \chi\right)\left[\alpha \mathrm{Tr}\left(\xi^\dagger \xi\right) + \beta\left(\phi^\dagger \phi\right) + \gamma\left(\sigma^\dagger \sigma\right)\right] \\ & + \left(\sigma^\dagger \sigma\right)\left[\zeta \mathrm{Tr}\left(\xi^\dagger \xi\right) + \epsilon\left(\phi^\dagger \phi\right) + \vartheta\left(\sigma^\dagger \sigma\right)\right]\,. \end{aligned} \tag{2}$$

Here $\psi_L(\mathbf{1},\mathbf{2},-1/2)$ and $\phi(\mathbf{1},\mathbf{2},-1/2)$, respectively, are the lepton and Higgs doublets, $\xi(\mathbf{1},\mathbf{3},2)$ is the Higgs triplet, $\sigma(\mathbf{1},\mathbf{1},0)$ and $\chi(\mathbf{1},\mathbf{1},0)$ are the light singlets, $\eta(\mathbf{1},\mathbf{1},0)$ denotes the heavy singlet [under the SM gauge group $SU(3)_c \times SU(2)_L \times U(1)_Y$]. Conventionally, we assign a lepton number $L = +1$ for the lepton doublets ψ_L while $L = 0$ for the Higgs doublet ϕ. In order to exactly conserve the lepton number, we further assign $L = -2$ for the Higgs triplet ξ, $L = +2$ for the heavy singlet η, $L = -1$ for the light singlet σ and $L = -2/3$ for the light singlet χ. Moreover, we impose a discrete Z_3 symmetry under which the light singlet χ is the unique field

with non-trivial transformation $[\chi \to \exp(i\frac{2\pi}{3})\chi]$ so that it is stable without nonzero vacuum expectation value (VEV).

For appropriate choice of parameters, the light singlet σ develops a VEV of about TeV, which breaks the global lepton number symmetry spontaneously. This VEV will, in turn, induce a small VEV of the heavy singlet η [16],

$$\langle\eta\rangle \simeq -\frac{\rho\langle\sigma\rangle^2}{M_\eta^2} \quad \text{for} \quad M_\eta \gtrsim \rho \gg \langle\sigma\rangle\,, \tag{3}$$

and hence a highly suppressed trilinear lepton number violating coupling of the Higgs triplet ξ to the Higgs doublet ϕ,

$$\mu = \kappa\langle\eta\rangle \simeq -\kappa\frac{\rho\langle\sigma\rangle^2}{M_\eta^2}\,. \tag{4}$$

Subsequently when the Higgs doublet ϕ develops a VEV to break the local electroweak symmetry, the Higgs triplet ξ will also pick up a tiny VEV [16],

$$\langle\xi\rangle \simeq -\frac{\mu\langle\phi\rangle^2}{m_\xi^2} \quad \text{for} \quad \mu \ll \langle\phi\rangle \lesssim m_\xi\,. \tag{5}$$

Clearly the suppressed coupling μ can guarantee the tiny VEV $\langle\xi\rangle$ although $m_\xi = \mathcal{O}(\text{TeV})$ is mildly bigger than $\langle\phi\rangle \simeq 174\,\text{GeV}$. Therefore the neutrinos eventually obtain their small Majorana masses through the Yukawa couplings of the Higgs triplet to the lepton doublets,

$$m_\nu = y\langle\xi\rangle\,. \tag{6}$$

In our model, the heavy singlet η has three decay channels:

$$\eta \to \xi^*\phi^*\phi^*\,, \quad \eta \to \chi^*\chi^*\chi^*\,, \quad \eta \to \sigma^*\sigma^*\,. \tag{7}$$

If the CP is not conserved, the above decays and their CP-conjugate can generate a lepton asymmetry stored in the Higgs triplet ξ, in the light singlet χ and in the light singlet σ, respectively, after the heavy singlet η goes out of equilibrium. As the fields ξ, χ and σ carry nonvanishing lepton numbers, these fields would store different types of lepton asymmetry. These three types of lepton asymmetry would decouple from each other as they are produced, although the total lepton asymmetry will be zero as a result of the exactly lepton number conservation. The generic features of these asymmetries are:

1. There is an asymmetry between the light singlet χ and its CP-conjugate. This asymmetry will survive since χ is not related to other lepton number violating interactions. We will show later this asymmetry can serve as the dark matter asymmetry to give a desired dark matter relic density.

2. The lepton asymmetry in the Higgs triplet ξ can be rapidly transferred to a lepton asymmetry in the lepton doublets ψ_L, as the lepton number conserving decay of ξ into two ψ_L is in equilibrium at this time. After the lepton number is spontaneously broken at the TeV scale, there will be a lepton number violating interaction of the Higgs triplet coupling to the Higgs doublet. This lepton number violation is extremely weak so that the induced lepton number violating processes will not go into equilibrium until the temperature is well below the electroweak scale. Therefore the lepton asymmetry stored in the lepton doublets could be partially converted to a baryon asymmetry by the sphaleron action before it is washed out by the lepton number violating processes [16]. Clearly this is a leptogenesis picture.

3. The lepton asymmetry in the light singlet σ will not affect the baryon asymmetry of the Universe as σ does not take part in the sphaleron process. Eventually we will have a relic density of a singlet Majoron, the massless Nambu-Goldstone boson corresponding to the global lepton number violation. This Majoron is harmless since its component from the Higgs triplet ξ is highly suppressed by $\langle\xi\rangle/\langle\sigma\rangle$.

For realizing a CP violation in the decays of the heavy singlet η, it is necessary that the tree-level diagrams interfere with the self-energy loop diagrams as shown in Fig. 1. We thus need at least two such heavy singlets η. Here we minimally introduce two heavy singlets $\eta_{1,2}$. For convenience, we choose the base of $\eta_{1,2}$ to give a real and diagonal mass matrix $M_\eta^2 = \text{diag}\left(M_{\eta_1}^2, M_{\eta_2}^2\right)$ and two real cubic couplings $\rho = (\rho_1, \rho_2)$ by a proper rotation. Consequently we only need to ensure $\kappa = (\kappa_1, \kappa_2)$ and $\lambda = (\lambda_1, \lambda_2)$ to be complex. In the limiting case where the two heavy singlets $\eta_{1,2}$ have hierarchical masses, the final lepton asymmetry stored in the Higgs triplet ξ and the dark matter asymmetry stored in the light singlet χ should mainly come from the decays of the lighter one. For illustration, let us focus on this hierarchical case. Without loss of generality, we choose η_1 to be the lighter heavy singlet and η_2 the heavier one. We then calculate the lepton asymmetry stored in the Higgs triplet ξ and the dark matter asymmetry stored in the light singlet χ from the decays of the lighter heavy singlet η_1. For simplicity, we assume

$$\frac{\kappa_i}{|\kappa_i|} \equiv \frac{\lambda_i}{|\lambda_i|} = e^{i\delta_i}\,, \tag{8}$$

and define $\delta \equiv \delta_2 - \delta_1$, so that we can easily read,

$$\begin{aligned}
\varepsilon_{\eta_1}^{L_{SM}} &\equiv 2\frac{\Gamma(\eta_1 \to \xi^*\phi^*\phi^*) - \Gamma(\eta_1^* \to \xi\phi\phi)}{\Gamma_{\eta_1}} \\
&= \frac{\sin\delta}{2\pi}\left|\frac{\kappa_2}{\kappa_1}\right|\frac{\rho_1\rho_2}{M_{\eta_2}^2 - M_{\eta_1}^2} \\
&\quad \times \frac{\frac{3}{32\pi^2}|\kappa_1|^2}{\frac{\rho_1^2}{M_{\eta_1}^2} + \frac{3}{32\pi^2}\left(|\kappa_1|^2 + |\lambda_1|^2\right)}\,, \qquad (9)
\end{aligned}$$

$$\begin{aligned}
\varepsilon_{\eta_1}^{\chi} &\equiv 3\frac{\Gamma(\eta_1^* \to \chi\chi\chi) - \Gamma(\eta_1 \to \chi^*\chi^*\chi^*)}{\Gamma_{\eta_1}} \\
&= -\frac{3\sin\delta}{4\pi}\left|\frac{\lambda_2}{\lambda_1}\right|\frac{\rho_1\rho_2}{M_{\eta_2}^2 - M_{\eta_1}^2} \\
&\quad \times \frac{\frac{3}{32\pi^2}|\lambda_1|^2}{\frac{\rho_1^2}{M_{\eta_1}^2} + \frac{3}{32\pi^2}\left(|\kappa_1|^2 + |\lambda_1|^2\right)}\,. \qquad (10)
\end{aligned}$$

It is straightforward to find the ratio between $\varepsilon_{\eta_1}^{L_{SM}}$ and $\varepsilon_{\eta_1}^{\chi}$,

$$\varepsilon_{\eta_1}^{L_{SM}} : \varepsilon_{\eta_1}^{\chi} = |\kappa_1\kappa_2| : -\frac{3}{2}|\lambda_1\lambda_2|\,. \qquad (11)$$

Here Γ_{η_i} denotes the total decay width of η_i or η_i^*,

$$\begin{aligned}
\Gamma_{\eta_i} &\equiv \Gamma(\eta_i \to \xi^*\phi^*\phi^*) + \Gamma(\eta_i \to \chi^*\chi^*\chi^*) \\
&\quad + \Gamma(\eta_i \to \sigma^*\sigma^*) \\
&\equiv \Gamma(\eta_i^* \to \xi\ \phi\ \phi\ ) + \Gamma(\eta_i^* \to \chi\ \chi\ \chi\ ) \\
&\quad + \Gamma(\eta_i^* \to \sigma\ \sigma\ ) \\
&= \frac{1}{8\pi}\left[\frac{\rho_i^2}{M_{\eta_i}^2} + \frac{3}{32\pi^2}\left(|\kappa_i|^2 + |\lambda_i|^2\right)\right]M_{\eta_i}\,, \qquad (12)
\end{aligned}$$

where the second equality is guaranteed by the unitarity and the CPT conservation.

For generating a lepton asymmetry stored in the Higgs triplet ξ and a dark matter asymmetry stored in the light singlet χ, the decaying particle η_1 should match the out-of-equilibrium condition [17]. For simplicity, we will consider the weak washout regime with

$$\Gamma_{\eta_1} \lesssim H(T)\Big|_{T\simeq M_{\eta_1}}\,, \qquad (13)$$

where

$$H(T) = \left(\frac{8\pi^3 g_*}{90}\right)^{\frac{1}{2}}\frac{T^2}{M_{\rm Pl}} \qquad (14)$$

is the Hubble constant with the relativistic degrees of freedom $g_* \simeq 100$ and the Planck mass $M_{\rm Pl} \simeq 10^{19}$ GeV. Furthermore, there will emerge a lepton number violating interaction between the Higgs triplet ξ and the Higgs doublet ϕ when the light singlet σ develops a VEV $\langle\sigma\rangle$ to spontaneously break the lepton number. The phase transition may occur at the temperature $T_c \lesssim \langle\sigma\rangle$. If the induced cubic coupling μ between the Higgs scalars is highly suppressed, specifically is much smaller than the mass of the Higgs triplet ξ, i.e. $\mu \ll m_\xi$, we have

$$\Gamma(\xi \to \phi^*\phi^*) = \frac{1}{16\pi}\frac{|\mu|^2}{m_\xi} \ll H(T)\Big|_{T=m_\xi}\,, \qquad (15)$$

so the lepton number violating processes can only go into equilibrium at a very low temperature and can not wash out the lepton asymmetry stored in the Higgs triplet ξ during the sphaleron epoch. The Higgs triplet ξ can thus transfer its lepton asymmetry to the lepton doublets ψ_L. Subsequently the sphaleron process will partially convert this lepton asymmetry to a baryon asymmetry.

The final baryon asymmetry and dark matter asymmetry would contribute energy density to the present Universe as below [17],

$$\begin{aligned}
\rho_B^0 &= n_B^0 m_N = \frac{n_B^0}{s_0}m_N s_0 = -\frac{28}{79}\frac{n_{L_{SM}}}{s}\Big|_{T\simeq M_{\eta_1}} m_N s_0 \\
&\simeq -\frac{28}{79}\varepsilon_{\eta_1}^{L_{SM}}\frac{n_{\eta_1}^{eq}}{s}\Big|_{T\simeq M_{\eta_1}} m_N s_0\,, \qquad (16)
\end{aligned}$$

$$\begin{aligned}
\rho_\chi^0 &= n_\chi^0 m_\chi = \frac{n_\chi^0}{s_0}m_\chi s_0 = \frac{n_\chi}{s}\Big|_{T\simeq M_{\eta_1}} m_\chi s_0 \\
&\simeq \varepsilon_{\eta_1}^{\chi}\frac{n_{\eta_1}^{eq}}{s}\Big|_{T\simeq M_{\eta_1}} m_\chi s_0\,. \qquad (17)
\end{aligned}$$

Conventionally, we define

$$\begin{aligned}
\eta_B^0 &= \frac{n_B^0}{n_\gamma^0} \simeq 7.04 \times \frac{n_B^0}{s_0} \\
&\simeq 7.04 \times \left[-\frac{28}{79}\varepsilon_{\eta_1}^{L_{SM}}\frac{n_{\eta_1}^{eq}}{s}\Big|_{T\simeq M_{\eta_1}}\right] \\
&\simeq -\frac{7.04\,\varepsilon_{\eta_1}^{L_{SM}}}{15\,g_*}\,, \qquad (18)
\end{aligned}$$

to describe the current baryon asymmetry. Here $m_N \simeq 1$ GeV is the masses of the nucleons, s is the entropy density, n_B, n_χ and n_γ, respectively, are the number density of baryon, dark matter and photon, $n_{\eta_1}^{eq}$ is the equilibrium distribution of the heavy singlet η_1. In the presence of fast annihilation between the dark matter and dark antimatter, the dark matter asymmetry should be equivalent to the dark matter relic density. In this scenario, the contributions from the baryonic and dark matter to the present Universe should have the following ratio,

$$\Omega_B : \Omega_\chi \equiv \rho_B^0 : \rho_\chi^0 = -\frac{28}{79}\varepsilon_{\eta_1}^{L_{SM}} m_N : \varepsilon_{\eta_1}^{\chi} m_\chi\,. \qquad (19)$$

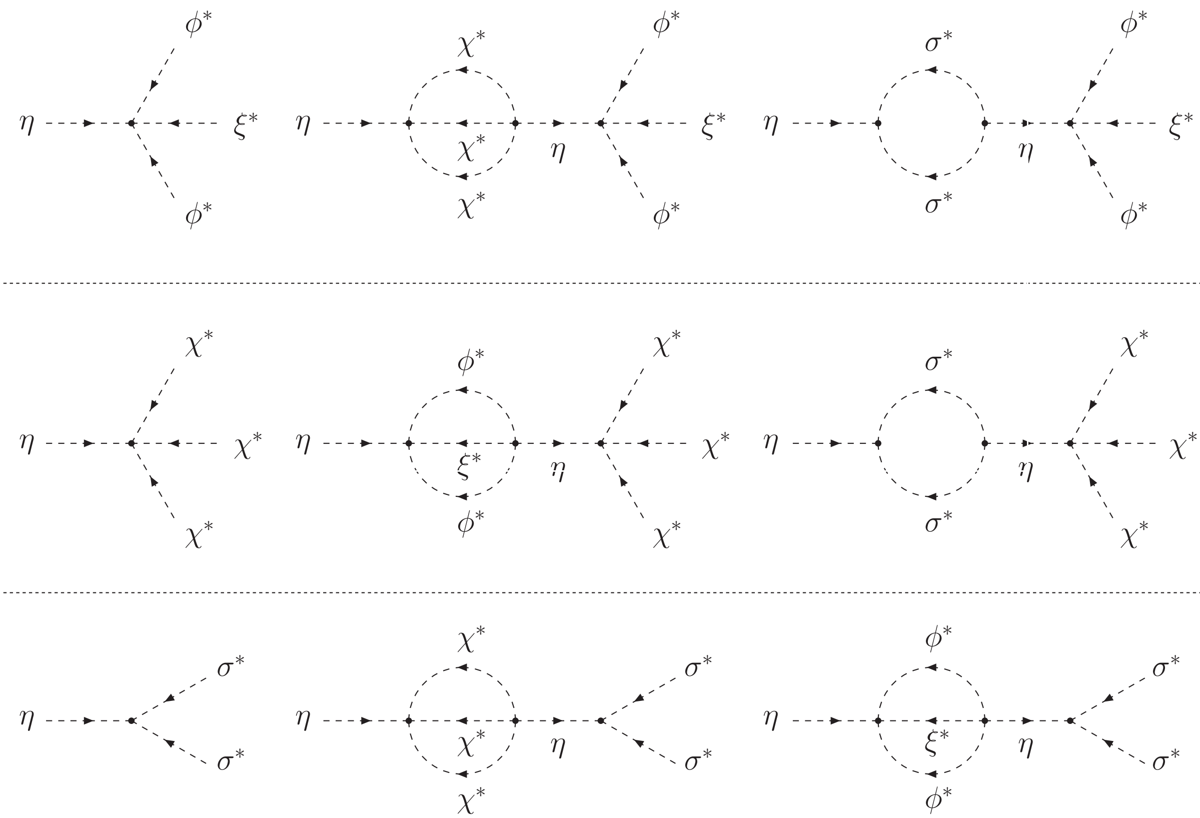

FIG. 1: The lepton number conserving decays of the heavy singlets η at tree level and loop orders for generating the lepton asymmetry stored, respectively, in the Higgs triplet ξ, in the light singlet χ and in the light singlet σ. The three types of lepton asymmetry decouple from each other as they are produced. The lepton asymmetry stored in the Higgs triplet ξ will be partially converted to the baryon asymmetry by the sphaleron process. On the other hand, the asymmetry between the light singlet χ and its CP-conjugate will survive as the relic density of dark matter.

For giving a numerical example, we take

$$\begin{aligned}
&M_{\eta_1} = 0.1 M_{\eta_2} = 4\times 10^{13}\,\mathrm{GeV}\,,\\
&\rho_1 = \rho_2 = 1.5\times 10^{12}\,\mathrm{GeV}\,,\quad \langle\sigma\rangle = 1\,\mathrm{TeV}\,,\\
&m_\xi = 540\,\mathrm{GeV}\,,\quad m_\chi = 7\,\mathrm{GeV}\,,\\
&|\kappa_1| = |\kappa_2| = 2.4|\lambda_1| = 2.4|\lambda_2| = 1\,,\\
&y = \mathcal{O}(1)\,,\quad \sin\delta = -0.075\,,
\end{aligned}\tag{20}$$

to output

$$\begin{aligned}
&\langle\chi\rangle \simeq -0.94\,\mathrm{eV}\,,\quad \mu \simeq -0.94\,\mathrm{eV}\,,\quad \langle\xi\rangle \simeq 0.1\,\mathrm{eV}\,,\\
&\varepsilon_{\eta_1}^{L_{SM}} \simeq -4\,\varepsilon_{\eta_1}^{\chi} \simeq -1.4\times 10^{-7}\,,
\end{aligned}\tag{21}$$

and then find

$$m_\nu \sim 0.1\,\mathrm{eV}\,,\quad \eta_B^0 \simeq 6.2\times 10^{-10}\,,\quad \Omega_\chi : \Omega_B \simeq 5\,,\tag{22}$$

which are well consistent with the experimental observations [1].

We now check if the annihilation between the dark matter and dark anti-matter is so fast that the dark matter relic density can be determined by the dark matter asymmetry. By taking into account that $\langle\sigma\rangle = \mathcal{O}(\mathrm{TeV})$ and $\langle\phi\rangle \simeq 174\,\mathrm{GeV}$, the thermally averaged cross section in the non-relativistic limit is easy to read,

$$\begin{aligned}
\langle\sigma v\rangle &= \frac{1}{32\pi}\left[3\left(\alpha - \frac{\gamma\zeta}{2\vartheta}\right)^2 + 2\left(\beta - \frac{\gamma\epsilon}{2\vartheta}\right)^2\right]\frac{1}{m_\chi^2}\\
&\quad + \frac{1}{16\pi}\left(\frac{4}{9} - \frac{\gamma}{2\vartheta}\right)^2 \frac{m_\chi^2}{\langle\sigma\rangle^4}\ \text{for } m_\chi = \mathcal{O}(\mathrm{TeV})\,,
\end{aligned}\tag{23}$$

$$\langle\sigma v\rangle = \frac{\beta^2}{4\pi}\sum_f N_f^c \frac{m_f^2}{m_h^4}\left(\frac{m_\chi^2 - m_f^2}{m_\chi^2}\right)^{\frac{3}{2}}\ \text{for } m_\chi = \mathcal{O}(\mathrm{GeV})\,.$$

Here f denotes the SM fermions with $m_f < m_\chi$, N_f^c is the number of colors of the f-fermion, h is the physical Higgs boson defined by $\phi = \frac{1}{\sqrt{2}}h + \langle\phi\rangle$. By inputting $\alpha,\beta,\gamma,\zeta,\epsilon,\vartheta < \sqrt{4\pi}$, the thermally averaged cross sec-

tion is flexible to reach a large value. For example, we obtain

$$\langle\sigma v\rangle = 22\,\mathrm{pb}\left(\frac{1\,\mathrm{TeV}}{m_\chi}\right)^2 ,$$
$$\langle\sigma v\rangle = 20\,\mathrm{pb}\left(\frac{7\,\mathrm{GeV}}{m_\chi}\right)^2\left(\frac{120\,\mathrm{GeV}}{m_h}\right)^4 . \quad (24)$$

for $\alpha,\beta,\gamma = 2$ and $\zeta,\epsilon,\vartheta = 1$. It is well known that the thermally produced dark matter with a mass from a few GeV to a few TeV should have a thermally averaged cross section slightly smaller than 1 pb to give a right relic density. If the thermally averaged cross section is too big, the relic density will be much below the desired value. This means in the present model, the thermally produced relic density is negligible so that the dark matter asymmetry can naturally be a very good approximation of the total relic density.

In the present scenario, our Universe will have mostly visible and dark matter and very little visible or dark antimatter, which is the main consequence of the models with common origin of visible and dark matter through their asymmetries. This means that the absence of decay or self-annihilation of dark matter will not result in the overclosure of the Universe. In the absence of the dark antimatter, the annihilation between the dark matter and dark antimatter can not leave any significant products although the cross section is very large. In this sense, the observed cosmic positron/electron excess [18, 19, 20, 21, 22] should be from continuum distribution of pulsars [23, 24] or should have their origin in our understanding of cosmic rays [25]. Consequently, the gamma-ray radiation from the final states in the dark matter annihilation is also absent. This is remarkably consistent with the observations of the galactic center [26] or the center of dwarf galaxies [27], which have already led to strong constraints on the flux of gamma-ray radiation.

The dark matter scalar χ has a quartic coupling with the SM Higgs doublet ϕ, i.e. $\beta\left(\chi^\dagger\chi\right)\left(\phi^\dagger\phi\right)$, as given in Eq. (2). The induced cubic coupling is

$$V \supset \sqrt{2}\,\beta\,\langle\phi\rangle\, h\,\left(\chi^\dagger\chi\right) . \quad (25)$$

Through the s-channel exchange of the physical Higgs boson, the dark matter is possible to find as a missing energy at colliders such as the CERN LHC [28]. On the other hand, the t-channel exchange of the physical Higgs boson will result in an elastic scattering of dark matter on nuclei and hence a nuclear recoil [28, 29]. The spin-independent cross section of the dark-matter-nucleon elastic scattering would be,

$$\sigma\left(\chi N\to\chi N\right) = \frac{\beta^2}{4\pi}\frac{\mu_r^2}{m_h^4 m_\chi^2} f^2 m_N^2 , \quad (26)$$

where $\mu_r = m_\chi m_N/(m_\chi+m_N)$ is the nucleon-dark-matter reduced mass, m_h is the mass of the physical Higgs boson, the factor f in the range $0.14 < f < 0.66$ with a central value $f = 0.30$ [29] parameterizes the Higgs to nucleons coupling from the trace anomaly, $f m_N \equiv \langle N|\sum_q m_q\bar{q}q|N\rangle$. For the dark matter mass within the range of 10 GeV to 1 TeV, we have

$$\sigma\left(\chi N\to\chi N\right)\simeq$$
$$\left[1.2\times10^{-39}\left(\frac{10\,\mathrm{GeV}}{m_\chi}\right)^2 - 1.7\times10^{-43}\left(\frac{1\,\mathrm{TeV}}{m_\chi}\right)^2\right]\mathrm{cm}^2$$
$$\times\frac{\beta^2}{4\pi}\times\left(\frac{f}{0.3}\right)^2\times\left(\frac{120\,\mathrm{GeV}}{m_h}\right)^4 , \quad (27)$$

which could be naturally below the current experimental limit [30, 31] and testable in the future experiments. Recently, the DAMA collaboration [32] has observed an annual modulation in the rates of nuclear recoil. If this signal is confirmed, it should be induced by the scattering of the dark matter particles from the galactic halo on the target nuclei in the detectors. The good fitting [33] on the DAMA data and the null results from other direct dark matter detection experiments [30, 31] opens a small window for the dark-matter-nuclei elastic scattering with the spin-independent cross section and the dark matter mass as below,

$$3\times10^{-41}\,\mathrm{cm}^2 \lesssim \sigma \lesssim 5\times10^{-39}\,\mathrm{cm}^2 , \quad (28)$$

$$3\,\mathrm{GeV}\lesssim m \lesssim 8\,\mathrm{GeV} . \quad (29)$$

In our model, the cross section (28) can be easily matched by inputting $\beta = \mathcal{O}(0.1-1)$, $0.14 < f < 0.66$ and $m_h = 120\,\mathrm{GeV}$ with the mass (29) to Eq. (26).

We now present the full version of our model to include the coincidence between the dark energy and the neutrinos. For simplicity, we only give the couplings relevant for our discussions,

$$\mathcal{L} \supset -\sum_{i,j,k,\ell=1}^{3}\left[\frac{1}{2}y_{ij}\overline{\psi^c_{L_i}}i\tau_2\xi_{ij}\psi_{L_j} + \kappa_{ij}\eta_{ij}\phi^T i\tau_2\xi_{ij}\phi\right.$$
$$+\lambda_{ij}\eta_{ij}\chi^3_{ij} + \omega_{ij}\zeta_{ij}\eta_{ij}\sigma^2 + \vartheta_{ijk\ell}\left(\zeta^\dagger_{ij}\zeta_{k\ell}\right)\left(\eta^\dagger_{ij}\eta_{k\ell}\right)$$
$$\left.+\mathrm{H.c}\right] . \quad (30)$$

Here ψ_L, ϕ, ξ, η, σ and χ keep the definitions in the simple version. The six SM singlets $\zeta_{ij} = \zeta_{ji}$ (without lepton number) have independent phase transformations to give a global $U(1)^6$ symmetry. In the presence of the

Yukawa couplings of the Higgs triplets to the lepton doublets (the first term in Eq. (30)), this $U(1)^6$ is explicitly broken down to its subgroup $U(1)^3$. So, there will emerge three massive pNGBs associated with the neutrino mass-generation after the six ζ_{ij} acquire their VEVs. The Coleman-Weinberg effective potential of these pNGBs would be

$$V = -\frac{1}{32\pi^2}\sum_{k=1}^{3} m_k^4 \ln\frac{m_k^2}{\Lambda^2}\,, \tag{31}$$

where m_k as a function of the pNGBs is the kth eigenvalue of the neutrino mass matrix m_ν, and Λ is the ultraviolet cutoff. A typical term in the potential V has the form,

$$V(Q) \simeq V_0 \cos\left(\frac{Q}{M}\right) \tag{32}$$

where Q is a pNGB combination with $M = \langle\zeta_{ij}\rangle$ and $V_0 = \mathcal{O}(m_\nu^4)$. It is well known that with M at the Planck scale $M_{\rm Pl}$, the pNGB field Q will acquire a mass of the order of $\mathcal{O}\left(m_\nu^2/M_{\rm Pl}\right)$ and thus can provide a consistent candidate for the quintessence [34, 35] dark energy.

In this paper we propose a variant of seesaw model that provides a common origin of the visible and dark matter and relates the dark energy to the neutrino masses. The same origin automatically implies that their contribution to the energy density of the present Universe is comparable. In this model, there is a dark matter asymmetry produced together with a lepton asymmetry that explains the baryon asymmetry via the sphaleron process. This dark matter asymmetry can account for the dark matter relic density because the annihilation between the dark matter and dark antimatter is so fast that the thermally produced relic density should be negligible. Although the annihilation between the dark matter and dark antimatter has a very large cross section, it is not required to prevent the overclosure of the Universe. In the absence of dark antimatter, currently the dark matter annihilation can't leave significant products, which should then provide a theoretical support to the alternate theories of the observed cosmic positron/electron excess. The dark matter scalar has a quartic coupling with the SM Higgs doublet so that it is expected to produce at the colliders and/or detect by the direct dark matter detection experiments. For example, the induced dark-matter-nucleon elastic scattering can explain the DAMA signal and the null results from other direct dark matter detection experiments. In our model, the neutrino masses are functions of the dark energy field, which will evolute with time and/or in space. In consequence, the neutrino masses are variable, rather than constant. The prediction of the neutrino-mass variation [10] could be verified in the experiments, such as the short gamma ray burst [36], the cosmic microwave background and the large scale structures [37], the extremely high-energy cosmic neutrinos [38] and the neutrino oscillations [39].

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[1] C. Amsler *et al.*, [Particle Data Group], Phys. Lett. B **667**, 1 (2008).
[2] M. Fukugita and T. Yanagida, Phys. Lett. B **174**, 45 (1986).
[3] P. Langacker, R.D. Peccei, and T. Yanagida, Mod. Phys. Lett. A **1**, 541 (1986); M.A. Luty, Phys. Rev. D **45**, 455 (1992); R.N. Mohapatra and X. Zhang, Phys. Rev. D **46**, 5331 (1992); M. Flanz, E.A. Paschos, and U. Sarkar, Phys. Lett. B **345**, 248 (1995); M. Flanz, E.A. Paschos, U. Sarkar, and J. Weiss, Phys. Lett. B **389**, 693 (1996); E. Ma and U. Sarkar, Phys. Rev. Lett. **80**, 5716 (1998); K. Dick, M. Lindner, M. Ratz, and D. Wright, Phys. Rev. Lett. **84**, 4039 (2000). For a review, see W. Buchmller, R.D. Peccei, and T. Yanagida, Annu. Rev. Nucl. Part. Sci. **55**, 311 (2005), and references therein.
[4] V.A. Kuzmin, V.A. Rubakov, and M.E. Shaposhnikov, Phys. Lett. B **155**, 36 (1985).
[5] V.A. Kuzmin, arXiv: hep-ph/9701269.
[6] R. Kitano and I. Low, Phys. Rev. D **71**, 023510 (2005).
[7] N. Cosme, L. Lopez Honorez, and M.H.G. Tytgat, Phys. Rev. D **72**, 043505 (2005).
[8] D.E. Kaplan, M.A. Luty, and K.M. Zurek, arXiv:0901.4117 [hep-ph].
[9] P.H. Gu, U. Sarkar, and X. Zhang, arXiv:0906.3103 [hep-ph].
[10] P. Gu, X. Wang, and X. Zhang, Phys. Rev. D **68**, 087301 (2003); R. Fardon, A.E. Nelson, and N. Weiner, JCAP **0410**, 005 (2004).
[11] X.J. Bi, P. Gu, X. Wang, and X. Zhang, Phys. Rev. D **69**, 113007 (2004); P. Gu and X.J. Bi, Phys. Rev. D **70**, 063511 (2004).
[12] R. Barbieri, L.J. Hall, S.J. Oliver, and A. Strumia, Phys. Lett. B **625**, 189 (2005); C.T. Hill, I. Mocioiu, E.A. Paschos, and U. Sarkar, Phys. Lett. B **651**, 188 (2007).
[13] P.H. Gu, H.J. He, and U. Sarkar, Phys. Lett. B **653**, 419 (2007); P.H. Gu, H.J. He, and U. Sarkar, JCAP **0711**, 016 (2007); P.H. Gu, Phys. Lett. B **661**, 290 (2008).
[14] P. Minkowski, Phys. Lett. **67B**, 421 (1977); T. Yanagida, in *Proc. of the Workshop on Unified Theory and the Baryon Number of the Universe*, ed. O. Sawada and A. Sugamoto (KEK, Tsukuba, 1979), p. 95; M. Gell-Mann, P. Ramond, and R. Slansky, in *Supergravity*, ed. F. van Nieuwenhuizen and D. Freedman (North Holland, Amsterdam, 1979), p. 315; S.L. Glashow, in *Quarks and Leptons*, ed. M. Lévy *et al.* (Plenum, New York, 1980),

p. 707; R.N. Mohapatra and G. Senjanović, Phys. Rev. Lett. **44**, 912 (1980).

[15] M. Magg and C. Wetterich, Phys. Lett. B **94**, 61 (1980); J. Schechter and J.W.F. Valle, Phys. Rev. D **22**, 2227 (1980); T.P. Cheng and L.F. Li, Phys. Rev. D **22**, 2860 (1980); R.E. Marshak and R.N. Mohapatra, in *Orbis Scientiae*, ed. A. Perlmutter and L.F. Scott (Plenum, NY, 1980), p. 277; S. Pakvasa, AIP Conf. Proc. **68**, 1164 (1980); G. Lazarides, Q. Shafi, and C. Wetterich, Nucl. Phys. B **181**, 287 (1981); R.N. Mohapatra and G. Senjanović, Phys. Rev. D **23**, 165 (1981).

[16] P.H. Gu, H.J. He, U. Sarkar, and X. Zhang, Phys. Rev. D **80**, 053004 (2009).

[17] E.W. Kolb and M.S. Turner, *The Early Universe*, Addison-Wesley, Reading, MA, 1990.

[18] J. Chang, *et al.*, [ATIC Collaboration], Nature **456**, 362 (2008).

[19] S. Torii, *et al.*, [PPB-BETS Collaboration], arXiv: 0809.0760 [astro-ph].

[20] O. Adriani, *et al.*, [PAMELA Collaboration], Nature **458**, 607 (2009).

[21] F. Aharonian *et al.*, [H.E.S.S. Collaboration], arXiv:0905. 0105 [astro-ph.HE].

[22] A.A. Abdo, *et al.*, [Fermi/LAT Collaboration], arXiv: 0905.0025 [astro-ph.HE].

[23] S. Profumo, arXiv:0812.4457 [astro-ph].

[24] V. Barger, Y. Gao, W.Y. Keung, D. Marfatia, and G. Shaughnessy, arXiv:0904.2001 [hep-ph].

[25] R. Cowsik and B. Burch, asXiv:0905.2136 [astro-ph.CO].

[26] L. Bergstrom, G. Bertone, T. Bringmann, J. Edsjo, and M. Taoso, arXiv:0812.3895 [astro-ph].

[27] R. Essig, N. Sehgal, and L.E. Strigari, arXiv:0902.4750 [hep-ph].

[28] J. McDonald, Phys. Rev. D **50**, 3637 (1994); C.P. Burgess, M. Pospelov, T. ter Veldhuis, Nucl. Phys. B **619**, 709 (2001).

[29] S. Andreas, T. Hambye, and M.H.G. Tytgat, JCAP **0810**, 034 (2008).

[30] J. Angle *et al.*, [XENON Collaboration], Phys. Rev. Lett. **100**, 021303 (2008).

[31] Z. Ahmed *et al.*, [CDMS Collaboration], Phys. Rev. Lett. **102**, 011301 (2009).

[32] R. Bernabei *et al.*, [DAMA Collaboration], Eur. Phys. J. C **56**, 333 (2008).

[33] F. Petriello and K.M. Zurek, JHEP **0809**, 047 (2008).

[34] N. Weiss, Phys. Lett. B **197**, 42 (1987).

[35] C. Wetterich, Nucl. Phys. B **302**, 668 (1988); P.J.E. Peebles and B. Ratra, Astrophys. J **325**, L17 (1988); B. Ratra and P.J.E. Peebles, Phys. Rev. D **37**, 3406 (1988).

[36] H. Li, Z. Dai, and X. Zhang, Phys. Rev. D **71**, 113003 (2005).

[37] A.W. Brookfield, C. van de Bruck, D.F. Mota, and D. Tocchini-Valentini, Phys. Rev. Lett. **96**, 061301 (2006).

[38] A. Ringwald and L. Schrempp, JCAP **0610**, 012 (2006).

[39] D.B. Kaplan, A.E. Nelson, and N. Weiner, Phys. Rev. Lett. **93**, 091801 (2004); V. Barger, P. Huber, and D. Marfatia Phys. Rev. Lett. **95**, 211802 (2005); M. Cirelli, M.C. Gonzalez-Garcia, and C. Pena-Garay, Nucl. Phys. B **719**, 219 (2005); V. Barger, D. Marfatia, and K. Whisnant, Phys. Rev. D **73**, 013005 (2006); M.C. Gonzalez-Garcia, P.C. de Holanda, and R.Z. Funchal, Phys. Rev. D **73**, 033008 (2006); T. Schwetz and W. Winter, Phys. Lett. B **633**, 557 (2006); P.H. Gu, X.J. Bi, B. Feng, B.L. Young, and X. Zhang, arXiv:hep-ph/0512076.